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Using supercluster geometry as a cosmological probe

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Abstract. We study the properties of superclusters detected in the Abell/ACO cluster catalogue. We identify the superclusters utilizing the ‘friend-of-friend’ procedure, and then determine supercluster shapes by using the differential geometry approach of Sahni et al. (1998). We find that the dominant supercluster morphological feature is filamentariness. We compare our Abell/ACO supercluster results with the corresponding ones generated from two different CDM cosmological models in order to investigate statistically which of the latter models best reproduces the observational results.

1. Introduction

The classical pattern of the distribution of matter on large scales supports the idea that the galaxy clusters are not randomly distributed but tend to aggregate in larger systems, the so called superclusters (Bahcall 1988 and references therein). Individual galaxy superclusters and their properties (shape, size etc) have been investigated by different authors (West 1989; Jaaniste et al. 1997 and references therein). It has been found that the vast majority of the superclusters are flattened triaxial objects, while Plionis, Valdarnini, & Jing (1992) found a preference for prolate (filament-like) superclusters.

In order to study in an objective manner the distribution of superclusters and their physical properties, it is necessary to develop objective algorithms and to apply them onto well controlled data. Indeed different methods like minimal spanning trees, shape statistics (Sahni & Coles 1995 references therein), genus-percolation statistics (Gout, Melt & Dickinson 1986) and Minkowski functionals (Mecke et al. 1994) have been used in order to describe the global geometrical and topological properties of the matter distribution utilizing angular and redshift surveys of galaxies as well as N-body simulations.

To this end, in this work, we utilize the Abell/ACO cluster catalogue in order: (i) to investigate whether we can reliably identify superclusters and measure their shapes in flux-limited galaxy samples, (ii) to measure the shape and size distribution of the Abell/ACO superclusters and (iii) to investigate whether these distributions can be used as a cosmological probe.

2. Data and Supercluster Detection

In our analysis we use the volume-limited sample of the Abell/ACO cluster catalogue, with $|b| \geq 30^\circ$ and limited within $315h^{-1}\text{Mpc}$ or $z \sim 0.11$ (see Einasto et al. 1997). As a result our sample contains ~ 926 clusters. In order to find the Abell/ACO superclusters, we use a very common procedure based on a ‘friend-of-friend’ algorithm. In particular, all mutually linked pairs (within a critical radius) are joined together to form groups (for those having common boundaries) and groups with more than two clusters are identified as candidate superclusters. To this end, the critical radius can be defined directly from the following equation (Peebles 2001):

$$R_{\text{cr}} \simeq \left(\frac{3 - \gamma}{\Omega_s \langle n \rangle r_o^\gamma} \right)^{\frac{1}{3-\gamma}} \quad (1)$$

where $\Omega_s \simeq 6.28$ steradians (solid angle), $\langle n \rangle \simeq 1.42 \pm 0.34 \times 10^{-5} h^3 \text{Mpc}^{-3}$ (the Abell/ACO mean number density) and $\gamma = 1.8$ with $r_o \simeq 20 \pm 2 h^{-1} \text{Mpc}$ (the correlation properties). Taking the latter parameters into account, we compute $R_{\text{cr}} \simeq 27 \pm 4 h^{-1} \text{Mpc}$ (in agreement with Einasto et al. 1997). Finally, using higher or much lower values of R_{cr} we tend to connect superclusters and percolate the whole volume.

2.1. Shape Statistics

Shapes are estimated for those “superclusters” that consist of 8 or more clusters, utilizing the moments of inertia (I_{ij}) method to fit the best triaxial ellipsoid to the data (Carter & Metcalfe 1980). We diagonalize the inertia tensor: $\det(I_{ij} - \lambda^2 M_3) = 0$ (where M_3 is 3×3 unit matrix), obtaining the eigenvalues $\alpha_1, \alpha_2, \alpha_3$ (where α_1 is the semi-major axis) from which we define the shape of the configuration since, the eigenvalues are directly related to the three principal axes of the fitted ellipsoid. The volume of each supercluster is then $V = \frac{4\pi}{3} \alpha_1 \alpha_2 \alpha_3$.

The shape statistic procedure, that we use, is based on a differential geometry approach, introduced by Sahni et al. (1998) [for application to the PSCz data see Basilakos, Plionis & Rowan-Robinson 2001]. Here we review only some basic concepts. A set of three shapefinders are defined having dimensions of length; $\mathcal{H}_1 = VS^{-1}$, $\mathcal{H}_2 = SC^{-1}$ and $\mathcal{H}_3 = C$, with S the surface area and C the integrated mean curvature. Then, it is possible to define a set of two dimensionless shapefinders K_1 and K_2 , as: $K_1 = \frac{\mathcal{H}_2 - \mathcal{H}_1}{\mathcal{H}_2 + \mathcal{H}_1}$ and $K_2 = \frac{\mathcal{H}_3 - \mathcal{H}_2}{\mathcal{H}_3 + \mathcal{H}_2}$, normalized to give $\mathcal{H}_i = R$ ($K_{1,2} = 0$) for a sphere of radius R . Therefore, based on these shapefinders we can characterize the morphology of cosmic structures (underdense or overdense regions) according to the following categories: (i) pancakes for $K_1/K_2 > 1$; (ii) filaments for $K_1/K_2 < 1$; (iii) triaxial for $K_1/K_2 \simeq 1$ and

(iv) spheres for $\alpha_1 \simeq \alpha_2 \simeq \alpha_3$ and thus $(K_1, K_2) \simeq (0, 0)$. For the quasi-spherical objects the ratio K_1/K_2 measures the deviation from pure sphericity.

3. The Geometrical Properties

In Figure 1 (left panel) we present the “shape spectrum” (broken line) and the multiplicity function (open symbols) of the identified superclusters. From the shape spectrum plot, it is obvious that the dominant feature of the Abell/ACO superclusters is filamentariness; ie., $K_1/K_2 < 1$ (in agreement with previous studies). Regarding extreme shaped superclusters, we have found, 4 very filamentary superclusters with $K_1/K_2 < 0.45$ (among which the Near Shapley and Hercules superclusters), 1 triaxial and 1 extreme pancake-like structures with $K_1/K_2 > 3$ (one of which is the Perseus-Pegasus supercluster).

To complement this, we utilize the completed IRAS flux-limited 60- μm redshift survey (PSCz) which is described in Saunders et al. (2000). We identify, in the smooth galaxy density field of the PSCz catalogue, high density regions (superclusters) and estimate their shapes (for details see Basilakos et al. 2001). In Figure 1 (right panel) we present a direct comparison of the PSCz and Abell/ACO geometrical properties, out to 240 h^{-1} Mpc. The two shape-profiles are in quite good agreement. This is a further indication that the two density fields are consistent with each other out to this distance.

3.1. Comparison with Cosmological Models

We use mock Abell/ACO catalogues (having similar to the observed Abell/ACO characteristics) generated from two large cosmological N-body simulations of Colberg et al. (2000), in order to investigate whether supercluster properties can discriminate between models. In particular, we consider two different cold dark matter models covering Hubble volumes, which are: (1) a flat low-density CDM model with $\Omega_\Lambda = 0.7$ and shape parameter $\Gamma = 0.17$, $h = 0.7$ and $L_{\text{box}} = 3000h^{-1}\text{Mpc}$ and (2) a critical density universe with $\Gamma = 0.21$ (τCDM), $h = 0.5$ and $L_{\text{box}} = 2000h^{-1}\text{Mpc}$. The CDM models are normalized by the observed cluster abundance at zero redshift; (Eke, Cole, & Frenk 1996). We average results over 64 ΛCDM and 27 τCDM independent mock Abell/ACO catalogues extending out to a radius of 315 $h^{-1}\text{Mpc}$. We analyse the mock Abell/ACO supercluster properties in the same fashion as that of the observed catalogue and we compare the outcome of this procedure in Figure 1 (left panel), where we plot the detected supercluster shape-spectrum and multiplicity function for two models and Abell/ACO data.

In order to quantify the differences between models and data we perform a standard χ^2 test, assuming Gaussianly distributed errors. This statistical test proves that the model which is excluded by the data, by the multiplicity function comparison, at a relatively high significance level is the τCDM model ($\mathcal{P}_{>\chi^2} = 3 \times 10^{-3}$), while the ΛCDM model reproduces the observed supercluster shape-spectrum and multiplicity function ($\mathcal{P}_{>\chi^2} = 0.80$). To validate our analysis we test the robustness of our method by comparing the models among themselves. We find that the shape-spectrum is insensitive to the different cosmologies, probably because supercluster shapes reflect the Gaussian nature of

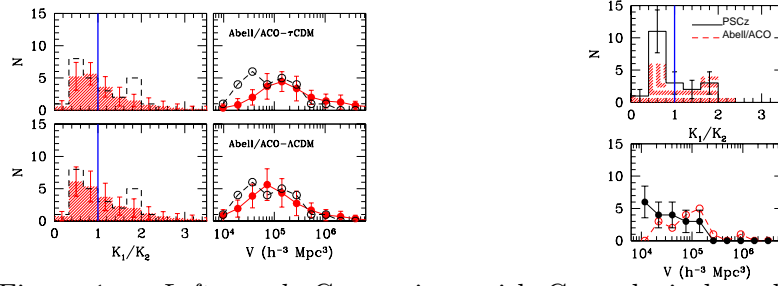


Figure 1. *Left panel:* Comparison with Cosmological models: The Abell/ACO results are represented by open symbols and broken lines. *Right panel:* Comparison between the Abell/ACO and the PSCz geometrical properties.

the initial conditions which are common to all models. However, the supercluster multiplicity function is a strong discriminant between the models.

4. Conclusions

We have studied the properties of superclusters detected in the Abell/ACO cluster catalogue. To determine supercluster shapes we use a differential geometry approach and find that the dominant supercluster morphological feature is filamentariness. Finally, we have compared our supercluster results with the corresponding ones generated from the analysis of two cosmological models (τ CDM and Λ CDM) and we find that the model that best reproduce the observational results is the Λ CDM model ($\Omega_\Lambda = 0.7$).

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